Renewable and Sustainable Energy Reviews 14 (2010) 1303–1311

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Wind energy in the Gulf of Tunis, Tunisia

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ARTICLE INFO

Article history:
Received 28 October 2009
Accepted 3 December 2009

Keywords:
Mean wind speed
Weibull distribution
Wind power potential
Wind rose
Turbulence intensity
Wind turbine

ABSTRACT

This paper presents a study of wind resource in the Gulf of Tunis. During 2008, an experimental measurement of wind speed and wind direction at 20 m and 30 m, were conducted using a 10-min time step. The statistic treatment of results permitted us to evaluate the most characteristics of wind energy in the studied site. An extrapolation of wind speed is, also, carried out using the deduced power law exponent. The annual production of the wind turbine Enercon E82 is estimated at a height of 100 m above ground level. The obtained results can be used to perform wind park project and confirm that the Gulf of Tunis has promising wind energy potential.

Contents

1. Introduction

During the last decades, oil price fluctuation caused an important problem in the economies of the importing countries. In fact, the vulnerability of oil-importing countries to higher oil prices varies distinctly, depending on the degree to which they are net importers and the oil intensity of their economies. To cure this problem, Tunisia decided to invest in the field of renewable energy and essentially the wind energy since it is localized in windy area. In 2000, the first wind farm in Tunisia was implemented in Sidi Daoud site, thanks to a financial support of the Global Environment Facility (GEF) and the United Nations Development Program (UNDP). Recently the Tunisian Company of Electricity and Gas (STEG) has signed a contract of 190 million Euros with the Spanish

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doi:10.1016/j.rser.2009.12.012

company Gamesa specialized in the construction of wind turbine, for the implantation of three new wind parks project in the site of Metline and Kechabta in the north Mediterranean coast [1]. In the end of 2009, the total power installed will reach a total capacity of 200 MW, which represents about 4% of the total electric power produced by STEG.

In this general context our study is devoted to the evaluation of wind energy potential in the central coasts of the Gulf of Tunis. Many researchers have shown interest in the estimation of the wind energy potential of several sites over the world. For example in Africa, we found the work of Ahmed Shata and Hannitch [2], which presents a data bank of electricity generation and wind potential assessment of Hargada in Egypt. Also, we found the study of Omer [3], which has estimated the wind energy resources of Sudan using the data collected over the country and proposed a study of wind pump profitability in the Soba site. In Europe, an estimation of wind resource in six locations of Hungary was conducted by Radics and Bartholy [4]. Migoya et al. [5] have also estimated the wind energy resource in Madrid region in Spain using the data collected by the Spanish National Meteorological Institute. In Asia, Rehman and Al-Abbadi [6] have interest in the turbulence intensity and wind shear coefficient in the site of Dhulom and their effect to the wind energy potential for the period of 4 year. An overview of the current state and future perspectives of the wind energy in China was presented in the work of Changliang and Zhanfeng [7]. In America, Wichsera and Klinkb [8] have collected the wind data in Minnesota over 3 years and evaluated the wind power potential in this part of the United States of America. In the Waterloo region in Canada, an investigation of wind characteristics and assessment of wind energy potential was presented by M. Li and X. Li [9]. In Tunisia, Elamouri and Ben Amara [10] purposed a study of 17 synoptic sites distributed on all the territory of Tunisia. Using the hourly meteorological data provided by the Meteorology National Institute (INM), they have evaluated the wind speed characteristics and the wind power potential at a height of 10 m above ground level. Ben Amar et al. [11] have presented the energy assessment of the first wind farm section of Sidi Daoud. The energetic and aerodynamic characteristics of aerogenerator Made AE-32 installed on site were also studied over 4 years.

In this study, measurements of wind speed and wind direction are conducted during the year of 2008, using a 10-min time step. The treatment of 52 704 observations, permitted us to evaluate the most important characteristics of wind energy in the studied site: the mean wind speed, the standard deviation of wind speed, the turbulence intensity and the mean wind power density. Wind rose, wind power rose and wind turbulence rose are also estimated.

2. Site description and experimental design

Tunisia is located in North Africa. It is bordered by Algeria to the west and Libya to the southeast. It is the northernmost country on the African continent, and the smallest of the nations situated along the Atlas mountain range (Fig. 1). The country is divided in two regions, the well-watered north and the semi-arid south. An abrupt southern turn of its shoreline gives Tunisia two faces on the Mediterranean sea with 1298 km coastline.

The experimental design is a NRG weather station installed in 36°43′04″N latitude and 10°25′41″E longitude (Fig. 2). It permits the measurement of wind speed, wind direction, ambient temperature and the solar flux in the Gulf of Tunis. This station is equipped with an acquisition system that record, every 10 min the average, the max, the min and the standard deviation values for each sensor.

Fig. 1. Geographic position of Tunisia.

3. Theoretical model

For a better understanding the wind speed variability, the data are usually presented in the form of frequency distribution. This gives us the information on the percent of time for which the velocity is within a specific range. Various probability functions can be suitable for statistical distributions of wind regimes. According to Gumbel [12], Weibull distribution is the best one, with an acceptable accuracy level. This function has the advantage of making it possible to quickly determine the average of annual production of a given wind turbine.

3.1. Weibull distribution

In Weibull distribution, the variations in wind velocity are characterized by the two functions:

- The probability density function.
- The cumulative distribution function.

The probability density function $f(V)$ indicates the percent of time for which the wind flows with a specific wind speed. It is expressed as

$$f(V) = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1}\exp\left(-\left(\frac{V}{A}\right)^{k}\right) \tag{1}$$

A and k are, respectively, the scale and the shape parameter. In order to determine the values of these parameters, the maximum likelihood method [13] can be used to fit a Weibull function to a measured wind speed distribution.

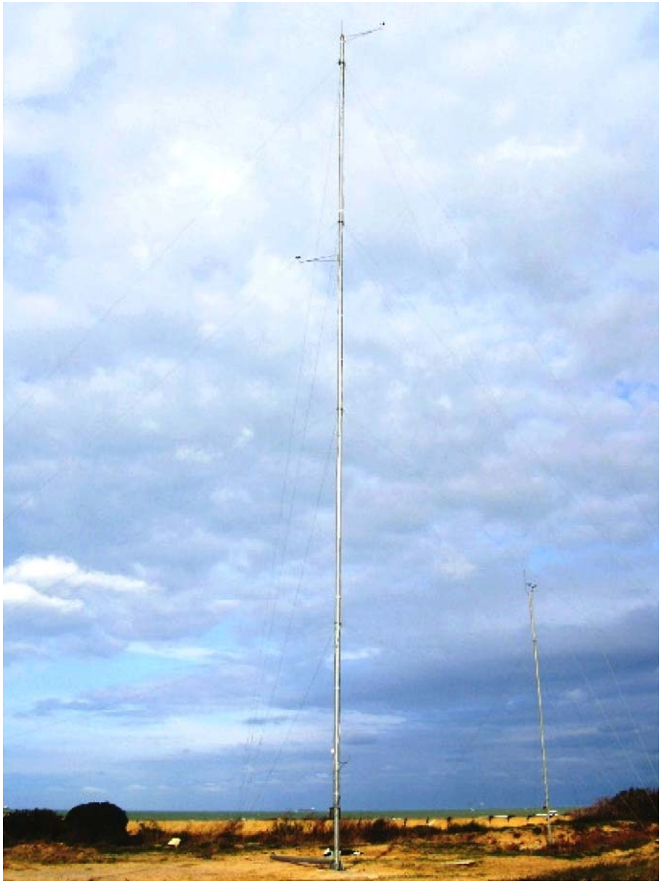

Fig. 2. Nrg weather station in the site.

In this method, the shape and scale factors can be calculated using these tow expressions [14]:

$$k = \left(\left(\frac{\sum_{i=1}^{n} V_i^k \ln(V_i)\, p(V_i)}{\sum_i V_i^k\, p(V_i)} \right) - \left(\frac{\sum_{i=1}^{n} \ln(V_i)\, p(V_i)}{p(V \geq 0)} \right) \right)^{-1} \tag{2}$$

$$A = \left(\frac{\sum_{i=1}^{n} V_i^k\, p(V_i)}{p(V \geq 0)} \right)^{(1/k)} \tag{3}$$

where n is the number of bins, V_i the wind speed central to bin i, $p(V_i)$ the wind speed frequency in bin i and $p(V \geq 0)$ the probability where the wind speed is higher or equal to zero.

The cumulative distribution function $F(V)$ is also called the cumulative density function or simply the distribution function, it gives us the percent of time that the wind velocity is equal or lower than the wind speed V. it is expressed by the integral of the probability density function.

$$F(V) = \int_0^V f(V) dV = 1 - e^{(V/A)^k} \tag{4}$$

3.2. Wind power density

For a period of measurement the mean wind power density in the site was given by the following expression:

$$\overline{P} = \frac{1}{2} \rho \overline{V^3} \tag{5}$$

They have mainly tow way to estimate the mean power density in the site, the first is based on the calculation of the energy pattern factor and the second on the probability distribution function. When a series of measurement is conducted in the site, the first method is mainly adapted, since it uses directly the collected data. The energy pattern factor K_e, which is the ratio of the available wind power density to the wind power corresponding to the cube of the mean wind speed, is expressed as

$$K_e = \frac{1}{N\overline{V}^3} \sum_{j=1}^{N} V_j{}^3 \tag{6}$$

N is the number of measurements, V_j the wind speed and $\overline{V}$ the mean wind speed.

So, the mean wind power density in the site will be given by the following relation:

$$\bar{P} = K_e \frac{1}{2} \rho \overline{V}^3 \tag{7}$$

The second method depends only in the availability of the probability distribution function in the site. Using the Weibull distribution, the mean wind speed is given by the following relation:

$$\overline{V} = \int_0^{\infty} V f(V)\, dV \tag{8}$$

And it can be expressed as

$$\overline{V} = A\Gamma\left(1 + \frac{1}{k}\right) \tag{9}$$

where Γ is the gamma function.
The associated standard deviation is

$$\sigma_V = A\left(\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right)^{0.5} \tag{10}$$

So, the wind power density will be expressed as

$$\overline{P} = \frac{\rho A^3}{2} \frac{3}{k} \Gamma\left(\frac{3}{k}\right) \tag{11}$$

Two important wind speeds can be estimated with this method, the first is the most frequently speed V_f and the second the most producible speed V_P.

For this reason we have to solve these two equations:

$$f'(V) = 0$$

$$\overline{P}'(V) = 0$$

We found that:

$$V_f = A\left(\frac{k-1}{k}\right)^{(1/k)} \tag{12}$$

and

$$V_P = \frac{A(k+2)^{(1/k)}}{k^{(1/k)}} \tag{13}$$

Once the wind power density is estimated, the wind energy density for a period of time will be calculated as

$$E = \overline{P} \cdot T \tag{14}$$

where T is the time period. For the annual wind energy density estimation the value of 8640 h is used.

3.3. Wind speed extrapolation

The wind speed measurements conducted in the site are estimated in 20 and 30 m. As known, the wind speed increase with altitude. Therefore, it is necessary to estimate the wind speeds at

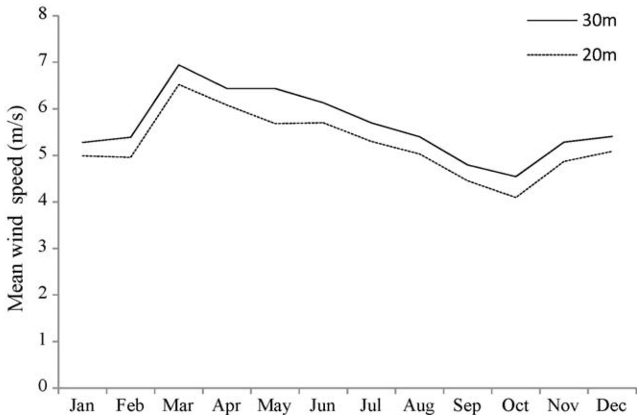

Fig. 3. Seasonal wind speed profile.

Table 1
Characteristics of wind speed and wind distribution at 30 m and 20 m.

	30 m	20 m
Scale parameter *k*	1.842	1.825
Ship parameter *A*	6.350	5.892
Mean wind speed (m/s)	5.641	5.236
The most frequently wind speed (m/s)	4.151	3.814
The most producible wind speed (m/s)	9.470	8.838

the various turbine hub heights for the study of the feasibility of the wind farm projects. There are two methods that can be used to adjust the wind velocity at one level to another level. One of them is the application of power law and the other is to employ the logarithmic law [15].

In this study the power law is used to estimate the wind speed at the altitude of 100 m using the following expression:

$$V = V_{mes}\left(\frac{h}{h_{mes}}\right)^{\beta} \tag{15}$$

where V_{mes} is the wind speed recorded at anemometer height h_{mes}, V is the wind speed to be determined for the desired heights h, β is the power law exponent estimated using the wind speed measurement at the tow altitude.

4. Experimental results

In this part of paper we are interested to the treatment of data recorded by the meteorological station installed on the site. The objective is to evaluate the most important characteristic of wind energy in the studied site. The statically treatments permit us to estimate the mean wind speed, the wind speed distribution function, the mean wind power density and the wind rose in the site at the altitude of 30 m and 20 m. Some local phenomena are also considered in the characterization of the site.

4.1. Wind speed

Fig. 3 represents the seasonal wind speed profiles. As shown, the tow curves have the same shape, only in the month of May where the difference between the mean wind speed at 30 m and 20 m go over 0.7 m/s. Higher values of mean wind speed are observed during Mars to June and essentially in Mars where the average wind speed exceed 7 m/s at the altitude of 30 m. However minimum mean wind speed values are measured in September and October. The maximum wind speed, equal to 20.6 m/s, is detected at the altitude of 30 m during the month of May.

4.2. Wind speed probability distribution function

The Table 1 illustrates the most important information about the probability distribution function at 30 m and 20 m. The ship and scale Weibull parameters are calculated using the modified maximum likelihood method expressed in Eqs. (2) and (3).

The Weibull probability distribution functions are than expressed by

$$f_{30}(V) = \frac{1.842}{6.35}\left(\frac{V}{6.35}\right)^{0.842}\exp\left(-\left(\frac{V}{6.35}\right)^{1.842}\right) \tag{16}$$

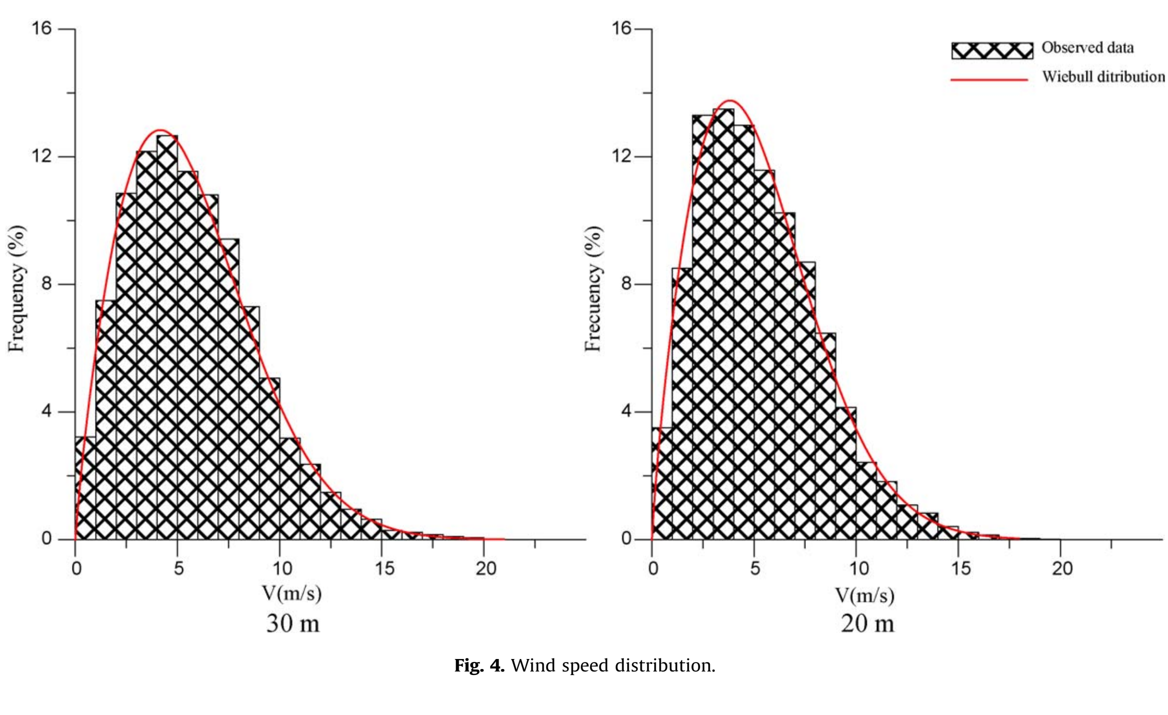

Fig. 4. Wind speed distribution.

Table 2
Energy pattern factor and mean power density at 30 m and 20 m.

	Measurement height (m)	
	30	20
Energy pattern factor	2.074	2.117
Mean wind speed (m/s)	5.647	5.233
Air density (kg/m^3)	1.224	1.224
Mean power density (W/m^2)	229	186

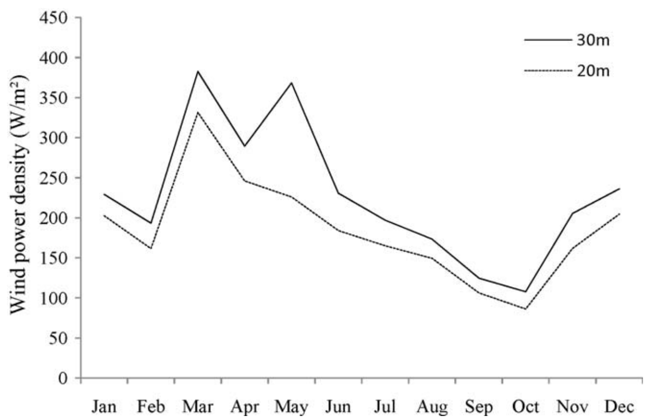

Fig. 5. Monthly wind power density.

and by

$$f_{20}(V) = \frac{1.825}{5.892}\left(\frac{V}{5.892}\right)^{0.825}\exp\left(-\left(\frac{V}{5.892}\right)^{1.825}\right) \tag{17}$$

We note that the difference between the estimated mean wind speed calculated using the Weibull distribution and the real mean wind speed in the site is about 10^{-3} m/s at the tow altitude. The most producible wind speed is equal to 9.470 m/s at the altitude of 30 m and 8.838 m/s at the high of 20 m.

As shown in Fig. 4, the Weibull function f_{30} reaches the top point at about 4.151 m/s with a value of about 12.841 (%), however the function f_{20} reaches the top point at the value of 3.814 m/s with the value of frequency equal to 13.766%.

4.3. Wind power density

As mentioned in the theoretical model they have mainly tow ways to estimate the power density in the site. The first is based on the measured data and the second on the probability distribution function. However, the first method is more precise since it uses the real data. For this reason we have estimated the energy pattern factor at the tow elevations and the associated wind power density (Table 2).

At the altitude of 30 m, the Monthly variation of wind power density shows a peak in the month of Mars and May, the mean power density attains a maximum value of about 380 W/m^2. However, at the altitude of 20 m the curve hit the highest value in the month of Mars where the mean power density reaches the value of 332 W/m^2. As shown in Fig. 5, the difference between the two curves in the month of May, equal to 138.45 W/m^2, is due to the gap in the associated mean wind speed as mentioned above.

4.4. Wind rose

Above we have estimated the mean wind speed and the mean wind power density without evoked the influence of the direction in the distribution of this parameter. In this section the frequency with which the wind direction falls within each direction sector are evaluated, so we present the data collected in the form of wind rose.

Fig. 6 shows that the prevalent wind blows from the west and southeast directions at each altitude with a percent of producible wind respectively equal to 26% and 28%. But the Table 3 proves that the west direction contributes with about 33% and 36% of the total available energy at 30 m and at 20 m respectively, however the southeast direction contributes with 28% at 30 m and only with 19% at 20 m.

These results can be confirmed in Fig. 7. In fact, the mean wind power density is equal to 370 W/m^2 in the west direction and to

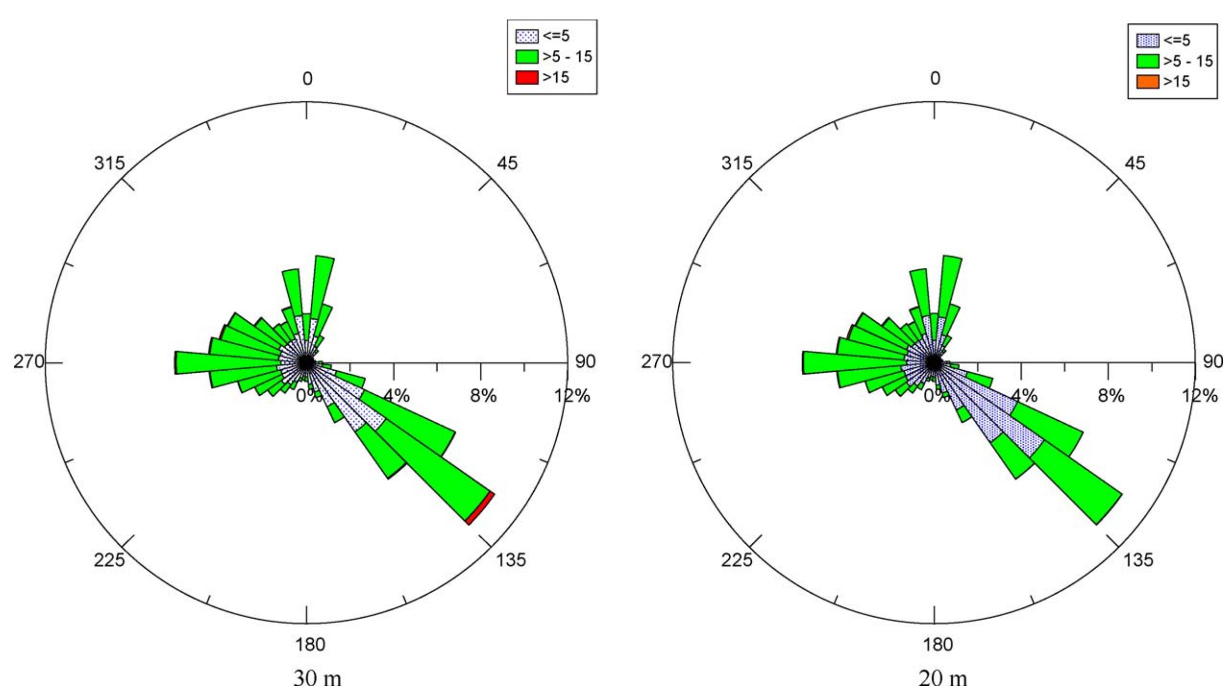

Fig. 6. Wind rose.

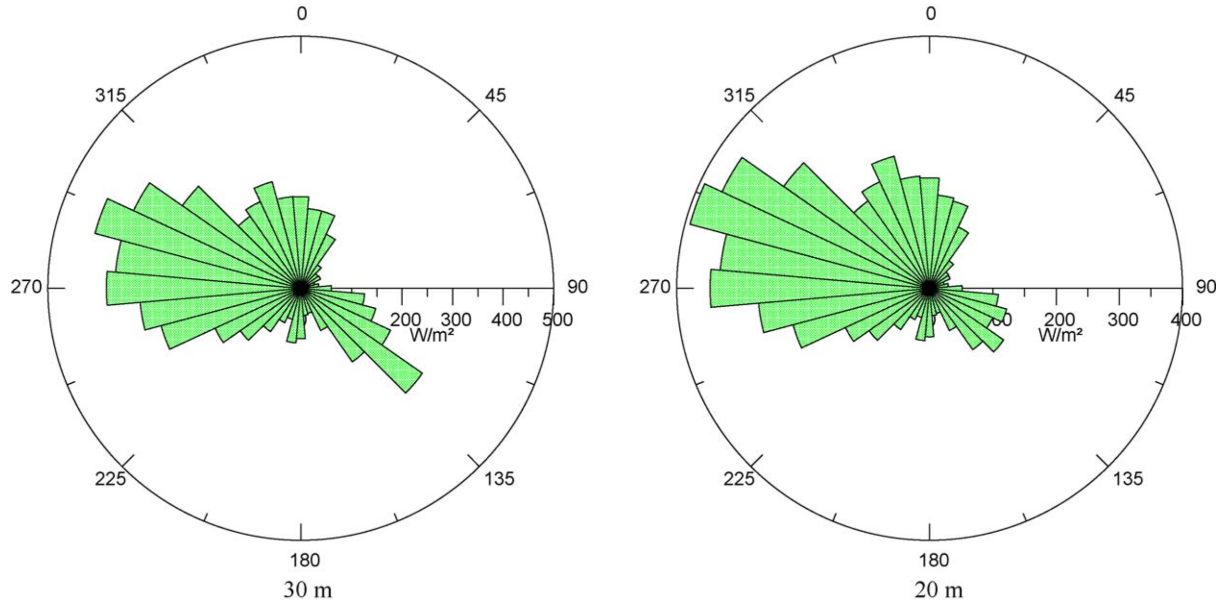

Fig. 7. Wind power density rose.

230 W/m^2 in the southeast direction at the altitude of 30 m. But at 20 m, it is equal respectively to 320 W/m^2 and to 121 W/m^2 in the west and the southeast direction.

4.5. Influence of sea breeze in the wind characteristic

The sea breeze is a wind from the sea that develops over land near coasts. It is formed when temperature differences between the land and the cost increase. During the course of the day, the sun heats the ground and the sea. But the heat capacity of water is far larger than that of soil, so it warms up more slowly than the lands surface. The land temperature rise progressively, which in turn starts heating the air from below, and warmer air rise due to buoyancy. The cooler air, with relatively higher sea level pressure, flows towards the land, creating a cooler breeze near the coast.

As shown in Fig. 9 the evolution of wind rose during the day can be divided in two parts. The most important part last from 10 h:00 to 18 h:00 and it is directly related to the phenomenon of sea breeze. In this period, the wind flows essentially from the north direction with a percent of producible wind that excides 20% between 14 h:00 and 16 h:00. The importance of this phenomenon can be shown, again, in the daily wind speed profile (Fig. 8), so we can confirm their highly contribution to the quantity of energy produced by a given wind turbine.

In the second period the wind flows from the west or the southeast direction in accord with the total wind rose. The producible wind flows essentially from the southeast direction in the period from 18 h:00 to 24 h:00, and from the west direction in the remain period of time.

4.6. Wind turbulence intensity

The turbulence intensity is a relative indicator for the turbulence intensity. It is important in the classification of the site according to the International Electro-technical Commission (IEC). For each 10 min the turbulence intensity is estimated using the following expression:

$$Ti = \frac{\sigma}{\overline{V}} \tag{18}$$

where σ is the standard deviation of the wind speed data sample and $\overline{V}$ is the mean wind speed.

The hourly and monthly average of *Ti* calculated using the mean wind speeds and corresponding standard deviation are provided in Figs. 10 and 11, respectively, for each altitude.

As can be seen from Fig. 10, higher values of *Ti* are observed during the period from midnight to 10 h:00 and lower during remain period of time. Also we can note that higher values of *Ti* were observed during September to December and smaller bit during rest of the month. In addition, the mean turbulence intensity $\overline{Ti}$ values in this site, equal to 9.8% at a wind speed of 15 m/s, indicate no concerns for wind energy exploitation according to the 3rd edition of the IEC 61400-1.

The turbulence rose (Fig. 12), shows that the $\overline{Ti}$ in the west and southeast direction does not exceed 16% for each altitude. These can confirm the previous results for the reason that *Ti* is lower than thee IEC standard turbulence limit in these directions. These

Table 3
Directional distribution of total available energy at 30 m and 20 m.

Direction	30 m	20 m
S–E (%)	27.75	18.80
W (%)	33.28	36.57
Other (%)	38.98	44.63

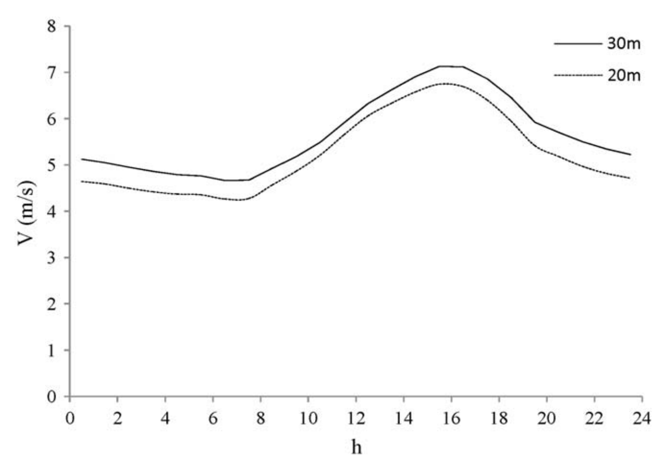

Fig. 8. Daily wind speed profile.

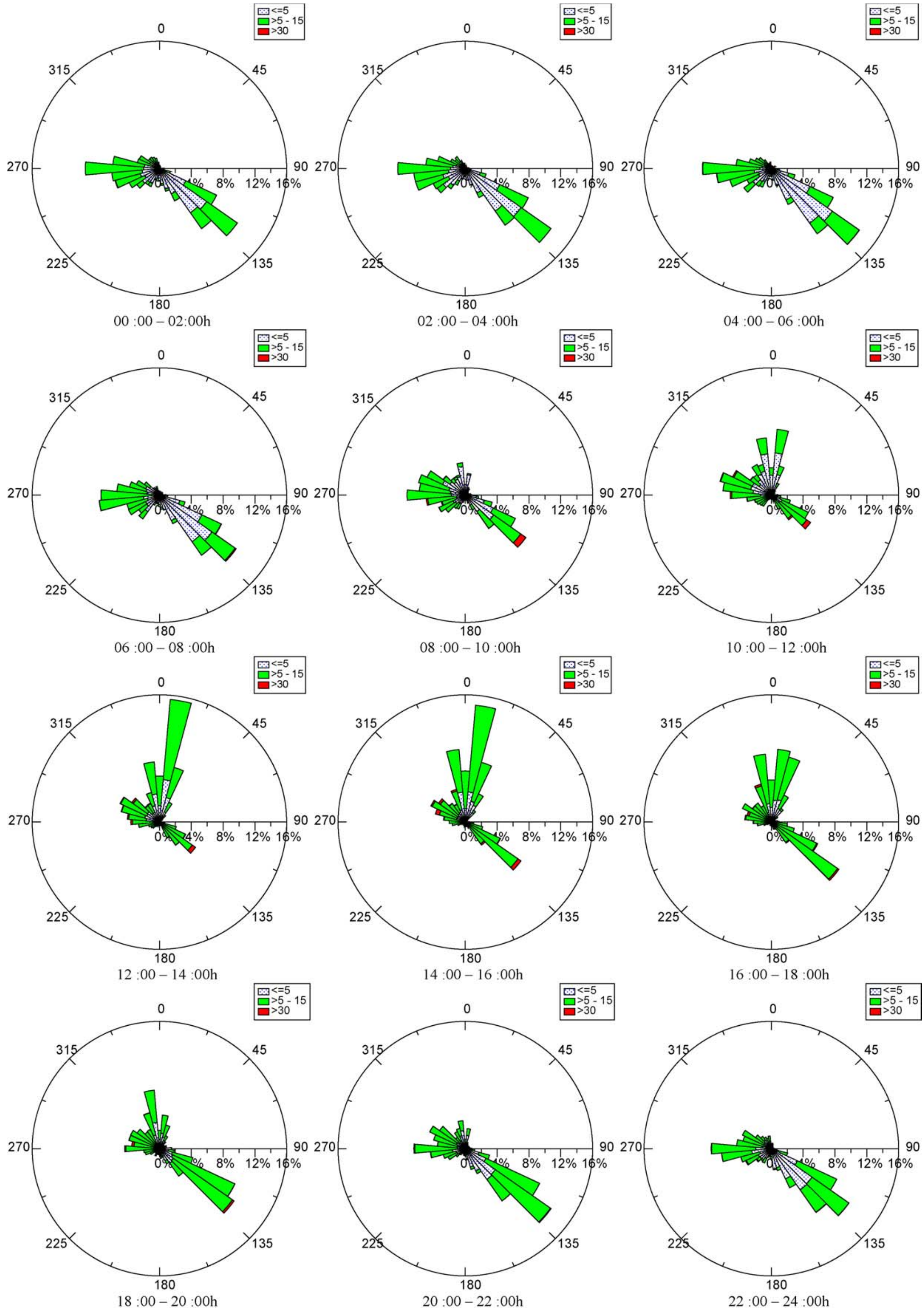

Fig. 9. Wind rose by time of day.

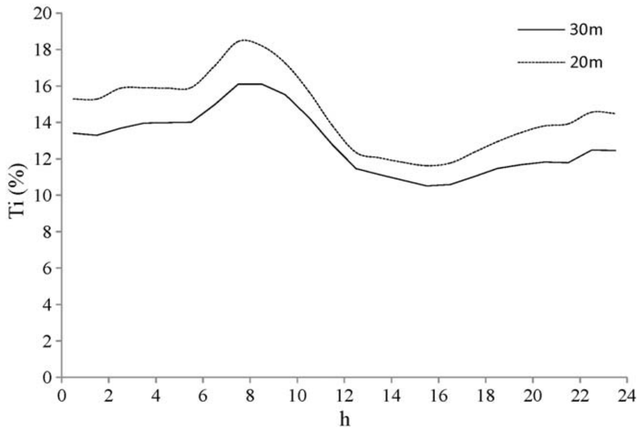

Fig. 10. Daily turbulence intensity profile.

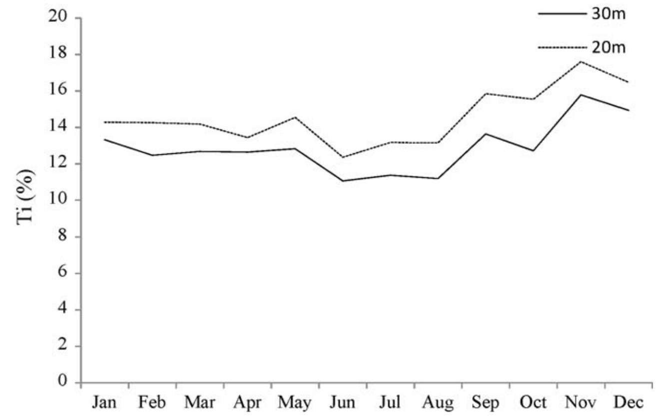

Fig. 11. Monthly turbulence intensity profile.

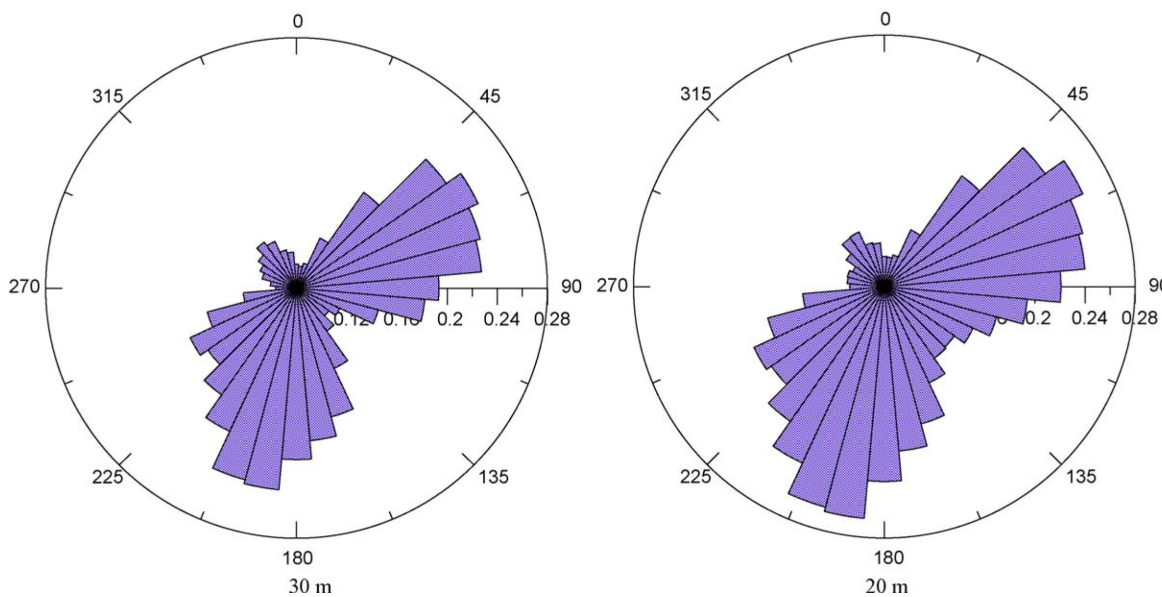

Fig. 12. Mean turbulence intensity rose.

minimize the percent of energy lost in kinetic energy of turbulence and protect blade for damage due to the fatigue problem.

5. Simulation of 2 MW wind turbine production

In this part of paper the production of the 2 MW wind turbine Enercon E82 was simulated. Every 10 min, the wind speed at 100 m is estimated using the power low exponent, equal to 0.185 in the site, and the recorded wind speed data. A procedure giving the energy production, based on linear interpolation and using the characteristic of wind turbine was developed. The characteristic of this wind turbine is given in Fig. 13.

The monthly production of the wind turbine Enercon E82 is given in Fig. 14. We note that March, April, May and June present the maximum of energy production in the site, so about 41.28% of total energy is produced in these months. The lowest values are observed during the month of September and October in agreement with the curve of the average wind speed.

Fig. 15 shows that the time at zero output $T0_{out}$ does not exceed 5% during the year. In fact, higher values of $T0_{out}$ are obtained in the month of January and December and lower values are observed in June, March and April. So, we can note that wind in this month is regularly with a high frequency of producible wind speed. These results are promising since they decrease the energy losses due to the electric network coupling and minimize considerably the use of other energy resource in the studied site.

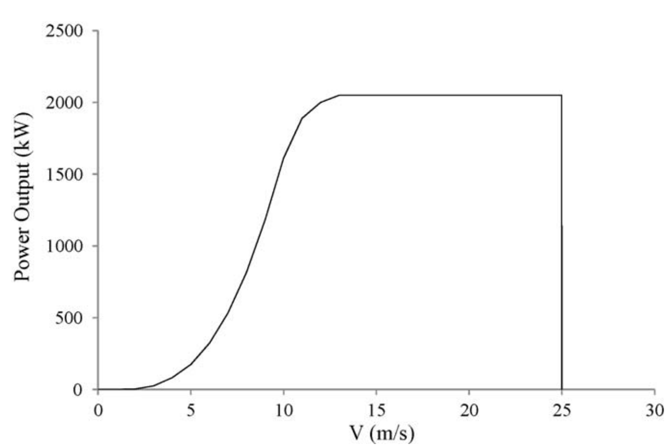

Fig. 13. Characteristic of the wind turbine Enercon E82

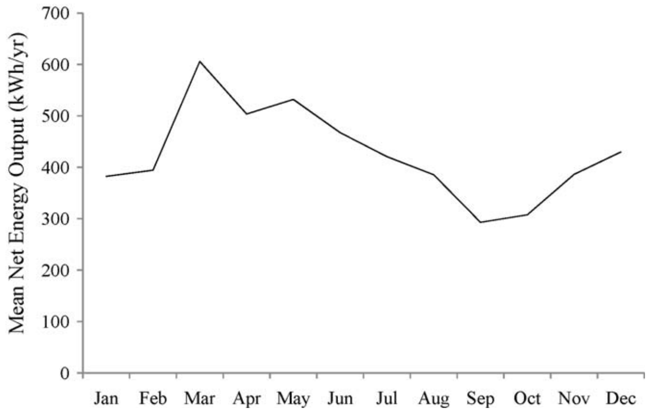

Fig. 14. Monthly production of wind turbine Enercon E82.

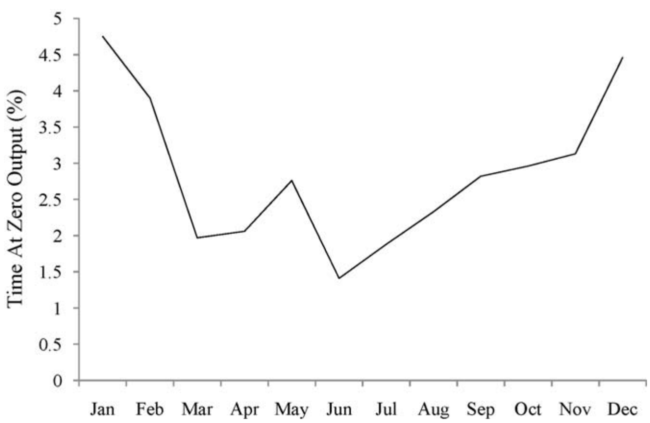

Fig. 15. Monthly percent of time at zero output.

6. Conclusion

In this study, we have evaluated the most important characteristics of wind energy in the central coast of the Gulf of Tunis. The measured and the deduced information show that the studied site presents an important wind resource in comparison with other sites over the world. The wind speed measured at two altitude permit us to estimate with good precision the wind power density at different altitude. The simulation of the production of many wind turbine permits to choose perfectly the type adapted to the site condition. So, with 5 108 700 kWh/year of energy production and 2.87% of time at zero output when using the wind turbine Enercon E82, we can classify the Gulf of Tunis as one of the most promising site in Tunisia according to the study released by Elammouri and Ben Amar [10]. We can confirm, again, that the wind energy in the site is of good quality since it is classified in the Turbulence Categories C according to the ICE standard classification. We have to note, again, that over 60% of total wind energy available in the site is extracted from the west and the southeast direction. These minimize the perturbation due to changes of the wind turbine direction.

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